Nutrient losses in surface irrigation runoff

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ABSTRACT: Runoff from surface-irrigated fields is typically managed to improve infiltration uniformity by reducing differences in infiltration opportunity times between the upper and lower ends of fields. Runoff water not used on other fields within an irrigation tract is discharged to streams or rivers, along with sediment and nutrients. Return flow nutrient and sediment concentrations may be greater than in the diverted water, but the total sediment and nutrient mass returned may be less if most of the diverted water infiltrates within the irrigation tract. Controlling erosion reduces total phosphorus loss, because total phosphorus concentration relates directly to sediment concentration. On-farm management practices, such as polyacrylamide (PAM) application and conservation tillage, reduce erosion from fields, while sediment ponds in the field or on return-flow streams trap suspended sediment that is not controlled by on-farm practices. Surface irrigation return-flow water quality can be improved with an organized effort using a combination of practices.

Keywords: Erosion, irrigation runoff, nutrient enrichment, phosphorus, sediment

Irrigation is important for reliable food production. Only 15% of the harvested cropland in the United States is irrigated, but almost 40% of the crop value is produced on the 20 million hectares (50 million acres) of irrigated land (National Research Council 1996). Half the irrigated land in the United States is surface-irrigated, and half the surface-irrigated land is furrow-irrigated, as opposed to border- or basin-irrigated (USDA 1998). The objective of this paper is to provide information about sediment and nutrient transport associated with surface-irrigated areas. Most of the data presented in this paper are from monitoring projects conducted in southern Idaho.

In contrast to rainfall, irrigation is not a random event; it is a scheduled activity with controlled application rates and durations. Farmers try to eliminate or control runoff caused by rain or sprinkler irrigation. Conversely, runoff is often planned with furrow irrigation to improve infiltration uniformity by reducing the difference in infiltration opportunity times between upper and lower ends of fields. Minimizing runoff requires careful management to set and adjust flow rates to match the unique conditions in each furrow. Twenty percent to 50% of applied water may run off a field, depending on crop, management, water supply, and field conditions (Berg and Carter 1980, Trout 1996). If irrigation water supply is low, for example, an irrigator may use low inflow rates so most of the applied water infiltrates and little or no runoff occurs. Consequently, the bottom end of the field will probably be under-irrigated. With poor management and abundant water supply, runoff may exceed 50%, which can cause excessive loss of soil and nutrients. Runoff water from surface-irrigated fields is often reused on downstream fields within an irrigation tract. Runoff that cannot be captured and reused is normally discharged to a river or other surface water body.

Soil erosion. Surface irrigation runoff transports sediment and nutrients from fields (Table 1). Sediment concentrations of 1,000 to 10,000 mg L^{-1} (1,000 to 10,000 ppm) are not uncommon in runoff from recently tilled, furrow-irrigated fields with silt loam soils and with poor management practices. Even with good management practices, sediment con-

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Table 1. Seasonal soil and phosphorus losses from 33 surface-irrigated fields in southern Idaho measured during the 1978 and 1979 growing seasons. Data from Berg and Carter (1980).

Parameter	Range	Median
Soil erosion (Mg ha^{-1})	0.45-141	7.8
Ortho-P (kg ha^{-1})	0.02-2.35	0.13
Total P (kg ha^{-1})	0.30-131	4.4

centrations may still exceed 100 mg L^{-1} (100 ppm), especially on row-crop fields. The total maximum daily load (TMDL) goal for the middle reach of the Snake River in Idaho is 52 mg L^{-1} (52 ppm) for suspended sediment. This goal will be difficult to achieve if applied as a standard to the end of surface-irrigated fields.

Sediment is detached and transported by water flowing in irrigation furrows. Most of the sediment detachment occurs on the upper quarter or third of surface-irrigated fields with uniform slopes (Trout 1996). Detached sediment either leaves the field with runoff or is deposited on the lower end of the field when furrow transport capacity decreases as water infiltrates. Continual topsoil removal from the upper ends of fields decreases topsoil depth (Figure 1), and reduces crop productivity (Figure 2) and profitability (Carter et al. 1985, Carter and Berg 1991).

Sediment losses as great as 145 Mg ha^{-1} (65 t a^{-1}) in 1 hr (Israelson et al. 1946) and 40 Mg ha^{-1} (18 t a^{-1}) in 30 min (Mech 1949) were reported in two early furrow-irrigation erosion studies. In a more recent study, annual sediment losses ranged from 0.5 to 141 Mg ha^{-1} (0.2 to 63 t a^{-1}) on 33 southern Idaho fields during one irrigation season (Berg and Carter 1980). Koluvek et al. (1993) reported soil losses of 0.2 to 50 Mg ha^{-1} (0.1 to 22 t a^{-1}) per season in Washington and 1 to 22 Mg ha^{-1} (0.4 to 12 t a^{-1}) per irrigation in Wyoming. Assuming 1,000 mm (40 in) of water are applied during an irrigation season with 20% runoff, a seasonal soil loss of 10 Mg ha^{-1} (4.4 t a^{-1}) would yield 5,000 mg L^{-1} (5,000 ppm) of sediment in irrigation runoff, which is almost 100 times greater than the TMDL goal of 52 mg L^{-1} (52 ppm) for the middle reach of the Snake River. Erosion rates are typically greater for row crops than close-seeded crops. Seasonal soil loss for row crops often exceeds 5 Mg ha^{-1} (2 t a^{-1}), whereas soil loss tends to be less than 2 Mg ha^{-1} (0.9 t a^{-1}) on close-seeded crops such as alfalfa (*Medicago sativa* L.) and small grains (Berg and Carter 1980). Soil erosion also increases with inflow rate and field slope (Figure 3). Increasing inflow rate 30% to 50% increased soil loss 3 to 10 times from two southern Idaho fields because both runoff volume and sediment concentration increased (Trout 1996).

Figure 1
Aerial photograph showing white soil on the upper end of a furrow-irrigated field that resulted from erosion during about 80 years of surface irrigation.

Phosphorus losses. Typically, greater than 90% of the total phosphorus (P) in surface irrigation runoff from clean-tilled row-crop fields is transported with eroded sediment. Conversely, when erosion is minimal from crops such as alfalfa and pasture, greater than 90% of the total P is dissolved in the runoff water (Berg and Carter 1980).

Total P concentration in surface irrigation runoff correlates directly with sediment concentration (Fitzsimmons et al. 1972, Westermann et al. 2001). Most eroded sediment has roughly 0.1% total P. Therefore, reducing sediment loss by 1 Mg will reduce total P loss by 1 kg (2 lb total P per ton of sediment). Dissolved reactive P concentration in surface irrigation runoff, on the other hand, correlates with soil test P concentration (Table 2), but not with sediment concentration (Westermann et al. 2001). Carter et al. (1971) measured lower dissolved P concentrations in subsurface drain return flow than in surface return flow, indicating that dissolved P was removed as water moved through soil to subsurface drains.

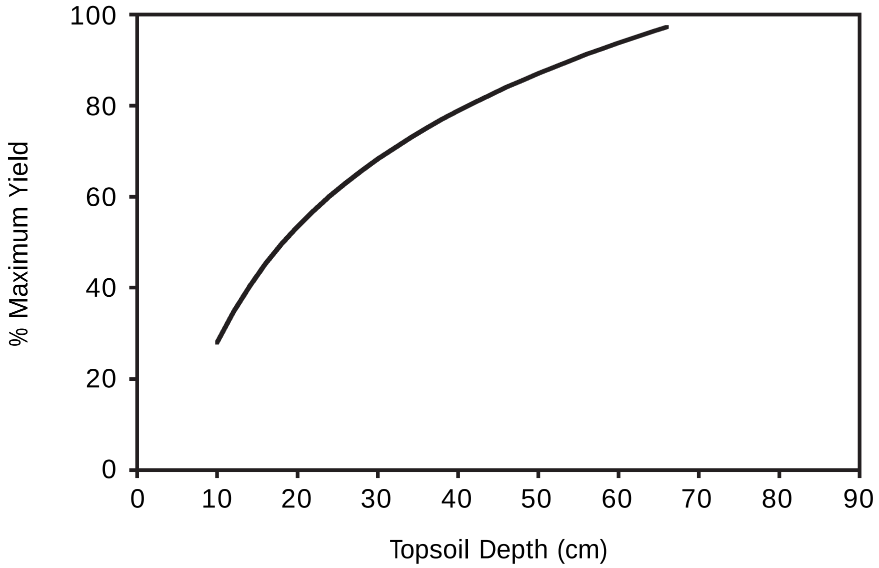
The TMDL goal for total P in the middle reach of the Snake River is 0.075 mg L^{-1} (0.075 ppm). Assuming transported sediment has a P concentration of 0.1%, this goal is equivalent to a sediment concentration of only 75 mg L^{-1} (75 ppm). This is 44% greater than the TMDL sediment goal of 52 mg L^{-1} (52 ppm), indicating that the P goal can be achieved by meeting the sediment goal.

Nutrient enrichment in irrigation return flow. Nutrient concentrations are usually greater in eroded sediment than in the soil from which it was eroded (Alberts and Moldenhauer 1981, Carter et al. 1974, Sharpley 1985). This nutrient enrichment occurs because eroded sediment typically contains more silt and clay-sized aggregates, which have greater nutrient concentrations than the larger sand-sized aggregates. Table 3 shows that sodium bicarbonate extractable P concentration associated with sediment in return-flow drains was 2 to 5 times greater than in field soil near the drains. The differences were not as great for total P, but the trend was the same.

An irrigation tract can be a sink for soluble or suspended elements as diverted water

Figure 2

Average relationship between percent maximum yield and topsoil depth for wheat, sweet corn and dry beans grown on farmer's fields and experimental plots. Data from Carter et al. (1985).



infiltrates within the tract. Bondurant (1971) measured similar nitrate, phosphate, potassium and sodium concentrations in furrow-irrigation inflow and return-flow water, but sediment concentration in return flow was typically two times greater than in the applied water. Because about 85% of the applied water infiltrated within the study area, the masses of sediment, nitrate, phosphate, potassium, and sodium in the return flow were less than in the applied water. The amount of sediment and nutrients retained within an irrigated tract was greater when the majority of the land was sprinkler-irrigated, because essentially all of the applied water infiltrated (Table 4). The Northside irrigation tract (north of the middle reach of the Snake River in southern Idaho), which was about 75% sprinkler-irrigated in 1971, retained 94% of the diverted water, as well as 79% of the sediment and 88% of the P that was transported with the diverted water. In contrast, the Twin Falls irrigation tract (south of the middle reach of the Snake River), which was about 90% furrow-irrigated in 1971, had less of the diverted water and P retained within the irrigation tract, as well as a net loss of sediment. In an earlier study on this irrigation tract, Carter et al. (1973) showed that salts were retained within the tract when only surface return flow was considered in the water balance. However, when the water balance also included estimated subsurface flow, there was a net loss of all elements except potassium and dissolved P (Table 5).

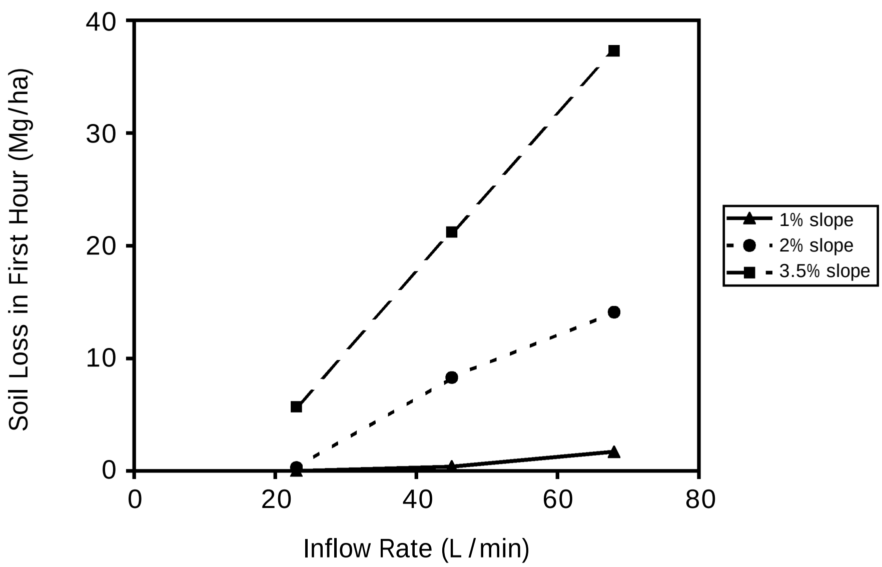
Management practices to improve surface-irrigation water quality. Water flowing over soil transports dissolved and detached nutrients, but implementing best management practices can minimize the negative effects of these nutrients in surface-irrigation return flow. Because total P concentration is directly related to sediment concentration, reducing sediment concentration will reduce total P concentration but may have little effect on dissolved P concentrations. Practices such as good inflow management, conservation tillage, polyacrylamide (PAM) application, filter strips, and sediment ponds can reduce sediment and nutrient losses from fields and decrease the amount of sediment and nutrients transported in irrigation return flow.

Good inflow management can minimize the amount of return-flow water while achieving acceptable infiltration uniformity within furrow-irrigated fields. Inflow management is subjective and probably requires more art than science to set and adjust inflow rates for specific conditions in each furrow. This also requires labor to check runoff and adjust inflow rates periodically during irrigation. Surge irrigation, which is the intermittent application of water to furrows, is a practice that can reduce runoff and improve infiltration uniformity (Allen and Schneider 1992, Evans et al. 1987). Blocking furrow ends to eliminate runoff can be an option if furrows are fairly large and field slope is low (e.g., <0.5%) so crops on the bottom end of the field are not inundated by the retained water.

Applying PAM with irrigation water or directly to furrow soil reduced soil erosion

Figure 3

Measured soil loss from 87 m (287 ft) long furrow segments during the first hour of irrigation with three inflow rates and furrow slopes. Data from Koluvek et al. (1993).



more than 90% on research plots (Lentz et al. 1992, Sojka and Lentz 1997, Trout et al. 1995). A conservative estimate for production fields is 50% to 80% reduction in soil loss. By reducing soil erosion, PAM treatment also reduced total P and chemical oxygen demand (COD) concentrations in runoff water (Lentz et al. 1998). Conservation tillage can also reduce soil erodibility and increase residue in furrows, both of which reduce soil loss to irrigation return flow (Carter and Berg 1991).

Maintaining a clean, deep ditch at the bottom end of a surface-irrigated field allows water to flow quickly from the field, but sediment concentration increases 2 to 3 times as water flows over the short steep slope where furrows enter the ditch (Carter and Berg 1983). Vegetative filter strips (about 4.5 m or 15 ft wide) on the bottom end of the field reduce erosion in return flow ditches and filter out some transported sediment and nutrients. Filter strips are marginally effective as a sole practice to reduce soil loss from furrow-irrigated fields. Excessive sediment deposition can cover and kill vegetation in the filter strip, reducing its effectiveness for trapping additional sediment. Filter strips are more effective when used in combination with on-field erosion control practices, such as PAM and conservation tillage, so the filter strips are not overloaded with sediment.

Sediment ponds remove suspended material from water by reducing flow velocity to allow particles to settle. Small ponds (e.g., 50 m^2 or 540 ft^2) may be constructed on individual fields, or large ponds (e.g., 5,000 m^2 or 54,000 ft^2) may be constructed on main return-flow streams. Sediment ponds also remove nutrients associated with sediment particles. A large pond removed 65% to 75% of the sediment and 25% to 33% of the total P that entered the pond (Brown et al. 1981). A smaller percentage of total P was removed because only the P associated with sediment was removed and a large portion of the total P flowing into the pond was dissolved. Dissolved P concentration may actually be greater in pond outflow than pond inflow because P may continue to desorb from sediment as water flows through the pond. In some locations, sediment ponds can be used as an irrigation water supply, further reducing the mass of sediment and nutrients flowing from the pond by decreasing the volume of water discharged.

Sediment concentration in field runoff may still exceed the 52 mg L^{-1} (52 ppm)

Table 2. Linear correlation coefficients between furrow runoff phosphorus concentrations and furrow soil phosphorus concentrations. Data from Westermann et al. (2001).

Runoff phosphorus‡	Furrow soil P test† $NaHCO_3$-P	FeO-P	Water-P
DRP	0.69*	0.74*	0.74*
FeO-P	0.68*	0.77*	0.59*
Total P	0.08	0.15	0.12

† $NaHCO_3$-P: bicarbonate-extractable inorganic phosphorus, FeO-P: iron-oxide impregnated paper-extractable phosphorus, Water-P: water-extractable inorganic phosphorus

‡ DRP: dissolved molybdate-reactive phosphorus, FeO-P: iron-oxide impregnated paper-extractable phosphorus from unfiltered water sample, Total-P: persulfate digestion phosphorus.

* Significant at 5% probability.

Table 3. Nutrient enrichment within two surface irrigation tracts. Data from Carter et al. (1974).

Irrigation tract	Soil $NaHCO_3$-P†	Soil Total P‡	Eroded sediment $NaHCO_3$-P	Eroded sediment Total P
	mg kg^{-1}			
Northside	24	722	134	1136
Twin Falls	22	839	47	962

† $NaHCO_3$-P is bicarbonate-extractable inorganic phosphorus.

‡ Total P is total phosphorus.

Table 4. Sediment and phosphorus balances for two southern Idaho irrigation tracts during the 1971 irrigation season. Data from Carter et al. (1974). The Northside tract is 65,350 ha, about 75% sprinkler-irrigated, and the Twin Falls tract is 82,030 ha, about 90% surface-irrigated in 1971.

Parameter	Northside Tract In	Out	Retained	Twin Falls Tract In	Out	Retained
Water (10^4 m^3)	151000	9040	94%	138000	37400 †	73%
Sediment (Mg)	57250	12080	79%	75800	114000	-50%
Ortho-P (Mg)	34.4	4.7	86%	28.6	25.7	10%
Total P (Mg)	159	19.3	88%	189	94.8	50%

† Includes flow from subsurface drains that enter return flow streams.

Table 5. Mean annual salt concentrations in surface and subsurface return flow and mean yearly change in soluble salts within the Twin Falls irrigation tract for October 1968 to September 1969. Data from Carter et al. (1973).

Element	Return-flow concentration surface mg L^{-1}	subsurface mg L^{-1}	Salt balance† kg ha^{-1}
Na^+	20.7	84.4	-580 ‡
K^+	4.7	5.8	15.2
Ca^{++}	21.8	85.4	-91.4
Mg^{++}	14.9	38.2	-170
Cl^-	22.7	52.3	-204
NO_3-N	0.12	3.24	-33.4
SO_4-S	14.5	48.0	-285
Ortho-P	0.07	0.01	1.0

† Total salt balance includes surface and subsurface return flow.

‡ Negative salt balance means total output exceeded total input or salt was exported from the irrigation tract.

Figure 4
Bottom end of a furrow-irrigated field with a 4.5 m (15 ft) wide vegetative filter strip and a 30 m^2 (320 ft^2) sediment pond.

TMDL goal with any one of these management practices. However, a combination of practices can be extremely effective and reliable. Using good inflow management in combination with PAM and/or conservation tillage will greatly reduce soil loss from a field. Filter strips protect the return-flow ditch at the bottom end of the field from erosion as runoff water flows from the field. A small sediment pond near the field outlet can trap additional sediment that was not controlled by other practices (Figure 4). Finally, larger sediment ponds and wetlands on return flow streams can remove sediment that was not stopped by on-farm practices or that was detached within return-flow streams (Figure 5).

Figure 5
A 0.2 ha (0.5 ac) sediment pond for trapping sediment from several fields.

Impact of implementing best management practices. Implementing sediment control practices on an 800 ha (2,000 ac) irrigation tract in the Columbia Basin of Washington reduced sediment and P discharges (King et al. 1982). Technical and financial assistance were provided to install sediment ponds, replace earthen ditches with pipe, and convert from furrow irrigation to sprinkler irrigation. Conversion to sprinkler irrigation reduced the amount of furrow-irrigated land from 88% in the first year of the study (1977) to 66% in the last year (1981). Irrigation return-flow volume only decreased 3% during the study, but sediment discharge decreased 80% and P discharge decreased 50%.

With an organized effort, irrigation return-flow water quality has gradually improved during the last 11 years on the Twin Falls irrigation tract, an 82,000 ha (203,000 ac) tract in southern Idaho (Table 6). From 1995 to 2001, the Twin Falls Canal Co. installed 98 sediment ponds on return-flow drains with total storage capacity of 11 ha-m (92 ac-ft). At the same time, farmers implemented best management practices on their fields, such as applying PAM and installing filter strips and small sediment ponds. About 75% of the farmers use PAM to some extent on their surface-irrigated row-crop fields. In addition, the percentage of sprinkler-irrigated land has increased from 15% in 1995 to 20% in 2000 as farmers convert from furrow irrigation to sprinkler systems. The Northside irrigation tract, a 65,000 ha (160,000 ac) tract also in southern Idaho, has also improved return-flow water quality by installing sediment ponds and wetlands. Because this irrigation tract is currently about 90% sprinkler-irrigated, the focus has been to reduce return-flow volume by better managing diverted water and installing pumps on several sediment ponds. These efforts must continue for irrigation return flow to meet the TMDL goals for the middle reach of the Snake River in southern Idaho.

Summary and Conclusions

Surface-irrigated fields often have runoff to improve irrigation uniformity. Water flowing over soil detaches and transports sediment and nutrients. Applying polyacrylamide and installing small sediment ponds on surface-irrigated fields, or converting from surface irrigation to sprinkler irrigation, are the most effective and acceptable practices at this time. Surface irrigation return-flow water quality

Table 6. Irrigation return-flow water quality for the Twin Falls irrigation tract. Data from personal communication with Clarence Robison (2001).

Year	Total suspended solids min	max	average	Total phosphorus min	max	average
	mg L^{-1}					
1990-91	45	410	193	0.15	0.51	0.29
1995	24	765	179	0.15	0.85	0.30
1998	31	472	130	0.11	0.51	0.22
2000	25	555	126	0.13	0.54	0.22
2001	23	184	80	0.08	0.29	0.17

can be improved by reducing runoff volume and soil erosion with on-farm management practices and trapping additional sediment in ponds on return-flow streams.

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